RESEARCH DEPARTMENT

A COLORIMETRIC STUDY OF A CONSTANT-LUMINANCE SYSTEM

Report No. T-093

(1962/28)

D. Maurice

W.N. Sproson, M.A.

(D. Maurice)

A COLORIMETRIC STUDY OF A CONSTANT-LUMINANCE SYSTEM

July 1962 Report No. T-093

(1962/28)

A COLORIMETRIC STUDY OF A CONSTANT-LUMINANCE SYSTEM

SUMMARY

The assessment of any system of colour television depends to some extent on the colours chosen for the test. Electronically generated colour bars may show faults which are non-existent in the transmission of ordinary pictures. A set of standard colours, which is typical of modern pigments and printing inks, is proposed for the purpose of assessing the colour and luminance fidelity of a colour television system.

The method is illustrated for a constant-luminance colour television system (proposed by James and Karwowski) under two conditions: (i) ideal analysis (ii) analysis by an existing colour scanner. The use of a uniform chromaticity diagram gives a convenient means of assessing the colour errors in subjective terms.

1. INTRODUCTION

One of the most convenient methods of testing colour television equipment involves the use of electronically-generated colour bars. In their simplest form, these produce, at the display, the primary colours red, green and blue (R, G, B) together with their complements yellow, magenta and cyan, at full saturation (100%) and at the maximum luminance consistent with a stated peak-white signal. Certainly any system or equipment that works well under these conditions (i.e., without overload or non-linear distortion) will operate well for all the colours (and their associated luminances) which are produced by ordinary scenes and whose R, G, B signals are generated either in a flying-spot scanner or a colour camera. However, this demand to withstand high levels of luminance and subcarrier amplitudes is in general an unnecessary extravagance and it would be more reasonable (and certainly more economic) to make a survey of present coloured materials and to decide on performance levels appropriate to the most "colourful" materials available. (Colourful for colour television means a combination of luminance and saturation since the subcarrier amplitude depends on the product of the two.)

Such a survey was made a short while ago and the thirteen colours* selected were those having maximum saturation consistent with reasonable luminance factors; this means that very saturated colours at (say) 1% luminance factor or less were not included. The list of colours (Table 1 and Fig. 1) shows that the lowest luminance factor is 1·5% in terms of a magnesium carbonate standard white, this is equivalent to 1·8% in terms of white paper (of 83% reflectance with respect to magnesium carbonate).

*all the colours selected were non-fluorescent.

TABLE 1

Thirteen "standard" colours

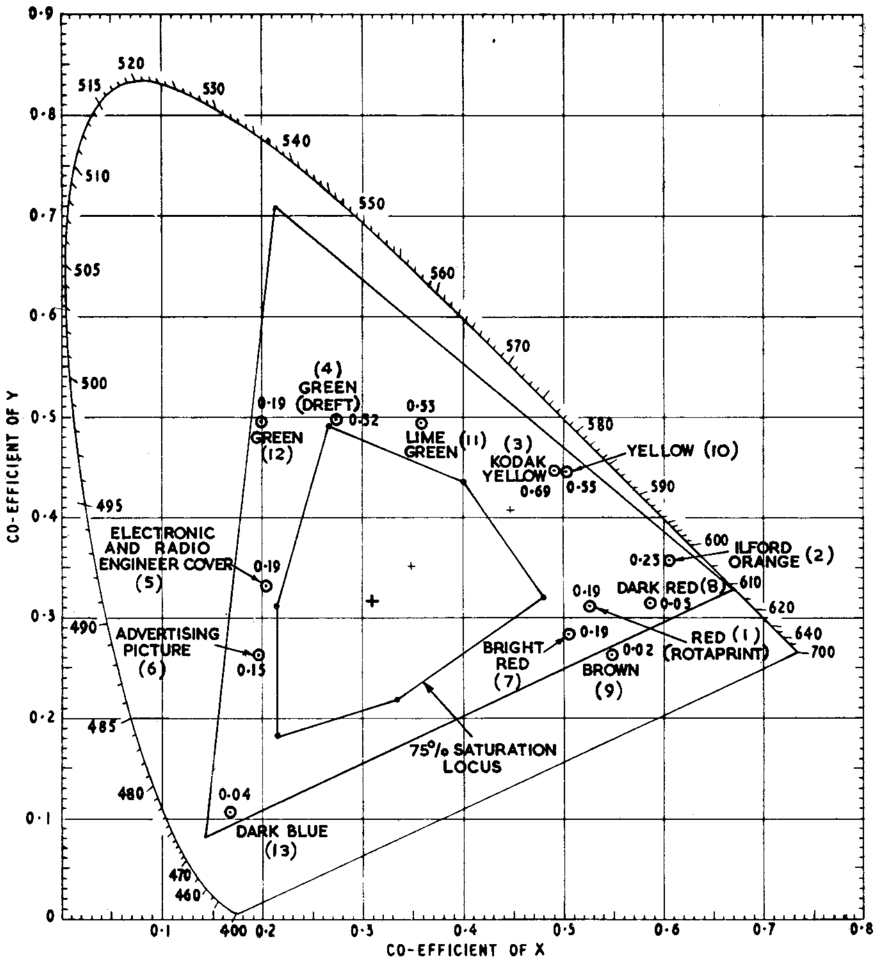
Colour	Chromaticity co-ordinates		Luminance factor (ref. $MgCO_3$)	Tristimulus values* ref. white paper			Saturation %
	x	y	Y	X	Y	Z	
1. Red Rotaprint	0·521	0·316	0·158	0·312	0·189	0·097	85·4
2. Orange Ilford	0·601	0·357	0·193	0·391	0·232	0·027	96·8
3. Yellow Kodak	0·493	0·447	0·576	0·762	0·691	0·093	95·6
4. Green Dreft	0·270	0·498	0·268	0·175	0·322	0·150	77·2
5. Blue-green (Electronic and Radio Engineer)	0·205	0·331	0·158	0·118	0·190	0·266	81·7
6. Blue (Advertising plate)	0·195	0·263	0·127	0·113	0·153	0·315	83·7
7. Bright red	0·503	0·283	0·161	0·342	0·192	0·145	91·4
8. Dark red	0·588	0·318	0·045	0·102	0·055	0·016	94·2
9. Brown	0·548	0·260	0·015	0·038	0·018	0·013	102·9
10. Yellow	0·500	0·455	0·458	0·603	0·549	0·054	97·7
11. Lime green	0·356	0·491	0·440	0·383	0·528	0·165	84·0
12. Green	0·200	0·497	0·154	0·074	0·184	0·112	96·2
13. Dark blue	0·161	0·106	0·037	0·068	0·045	0·311	95·0

White point = illuminant C

Saturation is specified in terms of the NTSC RGB triangle (see Fig. 1)

*white paper of reflection factor 0·833 with reference to $MgCO_3$ is regarded as a reasonable peak-white for a colour television scene

The chromaticity co-ordinates were computed from measurements of spectral reflectance taken on a Unicam spectrophotometer type SP 500 using the diffuse reflectance attachment. The measurements were taken at 10 mμ intervals in the range 400 to 740 mμ. A more extensive search might have revealed colours which are slightly more saturated (for a given luminance) nevertheless, the range given in Fig. 1 somewhat exceeds that quoted by Wintringham.[1] In the view of the writer, a colour television system should be tested using colours such as those shown in Table 1 and Fig. 1; however, it is not asserted that these specific colours are the optimum set (although it is considered that they are not far from such a set).



THE NUMBERS WRITTEN AGAINST THE COLOUR POINTS ARE LUMINANCE FACTORS WITH THE LUMINANCE FACTOR OF A WHITE CARD TAKEN AS 1.

Fig. 1 - Chromaticities of the thirteen standard colours

2. APPLICATION OF THE SET OF STANDARD COLOURS

2.1 Perfect Analysis with either Constant-luminance Emission and Normal NTSC Reception or Normal NTSC Emission and Reception

The R, G, B signals generated from the colours specified in Table 1 can be computed from the following matrix:

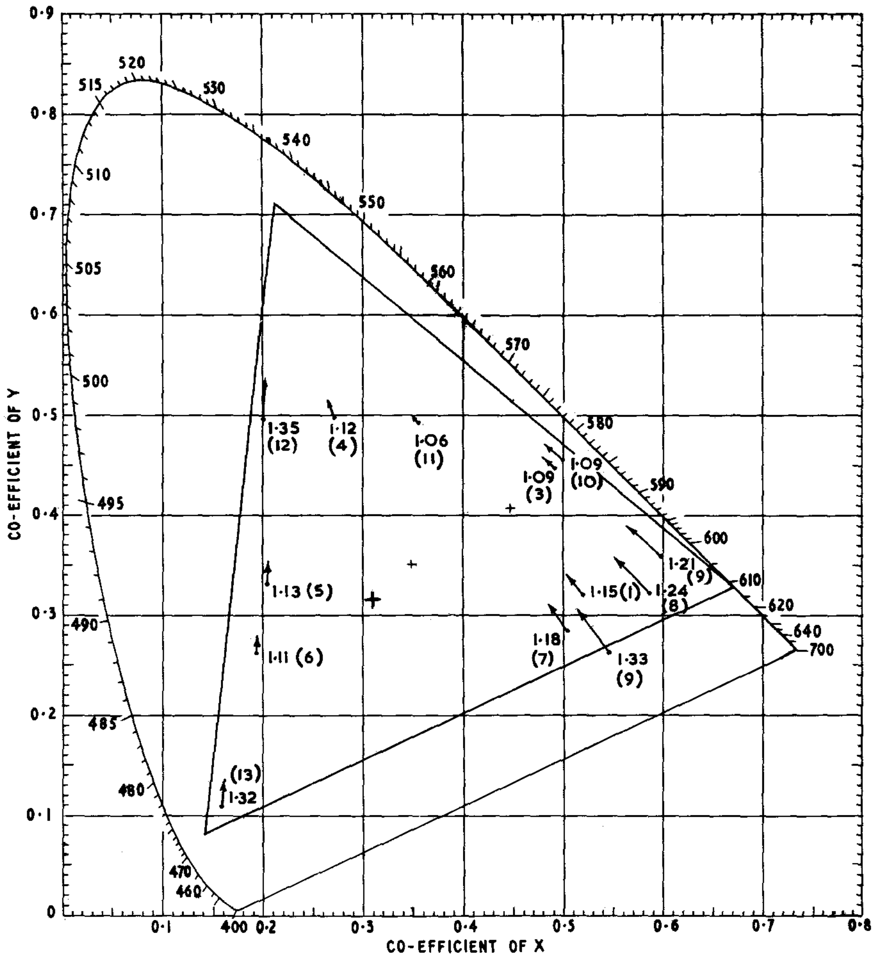
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1\cdot910 & -0\cdot532 & -0\cdot288 \\ -0\cdot985 & 1\cdot999 & -0\cdot028 \\ 0\cdot058 & -0\cdot118 & 0\cdot898 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

where X, Y, Z are the tristimulus values of the colours in Table 1.

This is based on the use of (i) standard NTSC synthesis primaries (ii) illuminant C for the white point and (iii) perfect analysis characteristics, including negative lobes.

The manner in which such a set of R, G, B signals would be processed in a constant-luminance system has been dealt with by James and Karwowski.[2] The result of applying these processes is given in Fig. 2 (compare this with Fig. 10 of James and Karwowski's paper, which shows the chromaticity and luminance errors which result from the NTSC reception of a "James and Karwowski emission").

A disadvantage of the standard C.I.E. chromaticity diagram is that equal distances in different parts of the diagram do not correspond to equally noticeable colour differences. A number of uniform chromaticity charts have been proposed in an attempt to overcome this difficulty and although no simple linear transformation appears to give a completely uniform chromaticity scale over the whole colour diagram, nevertheless a substantial improvement is possible. Thus the rectangular-uniform-chromaticity-scale[3] diagram reduces a variation of 20 to 1 in the original C.I.E.



ARROWS INDICATE REPRODUCED COLOUR, DOTS DEFINE THE CHROMATICITY OF THE ORIGINAL. THE NUMBERS AGAINST THE DOTS ARE RATIOS (F_2) OF REPRODUCED TO ORIGINAL LUMINANCE

Fig. 2 - Reproduction of the thirteen standard colours by standard NTSC receiver when receiving a constant-luminance emission (ideal analysis).

diagram to one of 4 to 1. The uniform chromaticity chart of MacAdam[4] achieves a similar result and has the advantage of representing a numerically simpler transformation, viz:

$$u = 2x/(6y - x + 1{\cdot}5) \qquad v = 3y/(6y - x + 1{\cdot}5)$$

where x and y are the chromaticity co-ordinates in the standard C.I.E. diagram and u and v are the corresponding co-ordinates in the MacAdam diagram. Fig. 3 shows the data of Fig. 2 plotted on the MacAdam uniform-chromaticity-scale diagram. In this diagram the length of the line drawn between the original and the reproduced colour is directly proportional to the noticeability of the colour difference with an accuracy as stated above. The errors are tabulated in units of just-noticeable-difference (j.n.d's) in Table 2, which also includes the luminance errors.

It should be noted that a standard NTSC transmission with a standard NTSC receiver would show no colour or luminance errors, except for colour No. 9 which is outside the R, G, B triangle. The principal defect of the NTSC transmission is that some of the luminance information is carried by the low-bandwidth chrominance channels, but reference to Fig. 1 of James and Karwowski's paper shows that for the twelve colours within the R, G, B triangle, the constant-luminance index (K_1) of the standard NTSC transmission is never less than 0·5 and has a mean value of 0·80. If colour

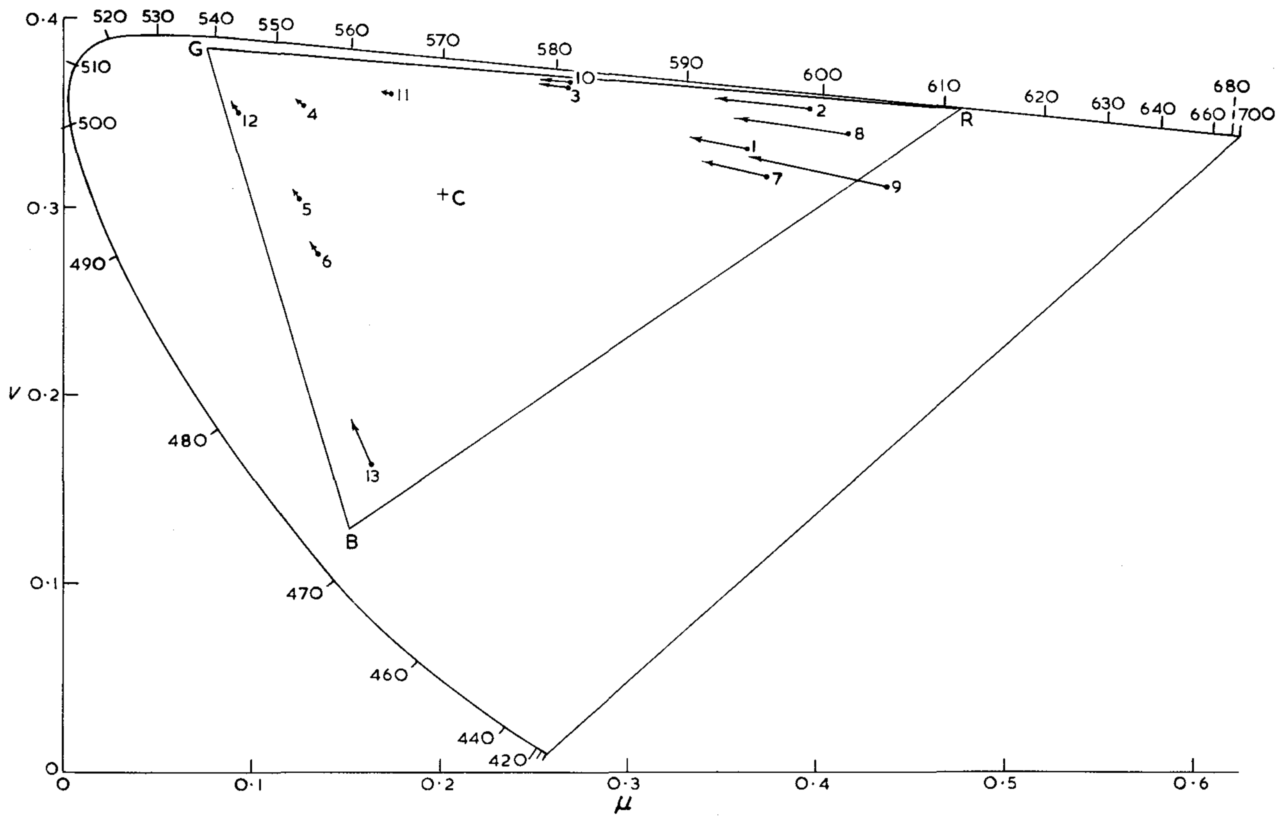


Fig. 3 - Data of Fig. 2 plotted on the MacAdam u-c-s diagram. The numbers refer to the colours as listed in the tables

TABLE 2

Chromaticity and luminance errors for ideal analysis, constant-luminance emission and NTSC reception

Colour	Chromaticity shift in j.n.d's	Luminance shift in j.n.d's
1. Red	8·6	6·7
2. Orange	14·1	9·2
3. Yellow	3·9	5·5
4. Green	1·6	6·0
5. Blue-green	2·1	5·9
6. Blue	2·3	4·2
7. Red	9·6	8·0
8. Red	16·7	5·6
9. Brown	19·8	4·7
10. Yellow	4·7	2·5
11. Green	1·3	1·7
12. Green	5·2	14·4
13. Blue	7·3	6·7
mean	7·5	6·2

Note that for ideal analysis, NTSC emission and NTSC reception the chromaticity (and luminance) shift is ZERO except for colour No. 9 where the chromatic error is 4 j.n.d.

No. 9 is included then the lowest value of K_1 becomes 0·33 and the mean value for the thirteen colours becomes 0·76. This implies that with existing saturated colours, a high proportion of the luminance signal is transmitted by the luminance channel and hence the definition is likely to be satisfactory.

2.2 Practical Analysis with either Constant-luminance Emission and Normal NTSC Reception or Normal NTSC Emission and Reception

The matrix shown in Section 2.1 applies only when the sensitivity curves describing the colorimetric analysis performed by the camera or the film scanner are ideal. In practice the sensitivity curves are usually restricted to the major positive parts and, although a fairly good approximation to these parts can be achieved, the absence of the subsidiary parts (both positive and negative) inevitably means the introduction of some errors. As an example, the sensitivity curves of a B.B.C. Research Department colour scanner were used and the colour reproduction was

estimated both for a normal NTSC emission and reception and also for the case of a constant-luminance emission with normal NTSC reception; the performance of this scanner was sufficiently good to permit side-by-side comparison of the original picture and a colour television reproduction during the 1956 demonstrations to Study Group XI of the C.C.I.R.

The results of this analysis for the constant-luminance emission, with normal NTSC reception, are shown by solid lines in Fig. 4. The dashed lines show the reproduction when the emission, as well as the reception, conforms to the NTSC standards. It will be seen that in some cases (e.g., colours 1 and 3), the errors of the constant-luminance system partially cancel the errors of analysis. In general, however, the errors produced by the constant-luminance system are greater than those produced by colour analysis, and Table 3 shows that the mean colour error increases from 5·1 j.n.d's to 8·0 j.n.d's.

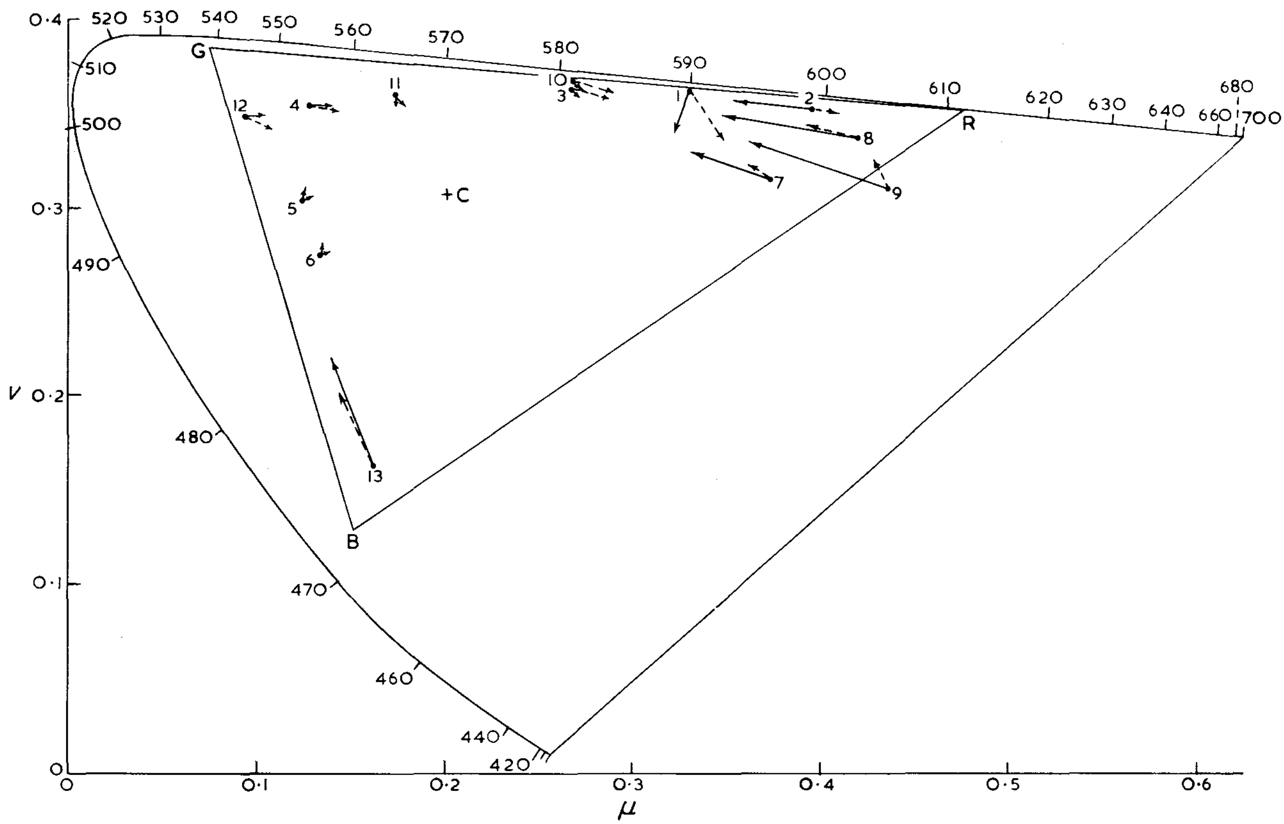


Fig. 4 - Reproduction of original colours using practical analysis. Solid lines connect original and reproduction obtained with a constant-luminance emission and standard NTSC receiver. Dashed lines connect original and reproduction obtained with a standard NTSC transmission and a standard NTSC receiver

TABLE 3

Chromaticity and luminance errors for a case of practical analysis with NTSC reception

Colour	NTSC emission		Constant-luminance emission	
	Chromaticity shift in j.n.d's	Luminance shift in j.n.d's	Chromaticity shift in j.n.d's	Luminance shift in j.n.d's
1. Red	8·8	4·1	6·8	10·0
2. Orange	3·4	0·5	11·5	10·0
3. Yellow	5·7	9·5	1·6	4·6
4. Green	4·2	2·1	2·9	6·0
5. Blue-green	1·6	4·1	2·3	8·8
6. Blue	1·0	3·5	1·8	6·4
7. Red	3·9	4·6	12·2	11·5
8. Red	7·3	5·6	19·3	9·9
9. Brown	4·7	3·0	20·8	7·1
10. Yellow	6·5	5·1	2·1	2·4
11. Green	2·3	2·4	1·6	1·2
12. Green	4·9	3·7	3·1	11·5
13. Blue	11·7	10·0	18·2	14·7
mean	5·1	4·5	8·0	8·0

3. DISCUSSION OF COLOUR REPRODUCTION WHEN USING THE CONSTANT-LUMINANCE SYSTEM WITH THE NTSC RECEIVER

The effect of receiving the constant-luminance emission on a normal NTSC receiver is invariably to add a spurious green signal. This means that all the errors (Figs. 3 and 4) are in the same direction, in spite of the fact that the neutral scale is correctly reproduced. Thus the picture will have the appearance of a green trend in colour balance and it is perhaps unfortunate that observers do not like colour pictures which are distorted in either the green or magenta direction (e.g., consider the effect on flesh tones). The eye is much more tolerant to changes in the orange-to-cyan direction particularly when this coincides with the black-body locus.

The red primary suffers considerable distortion and in fact becomes a yellowish-orange of dominant wavelength 596 $m\mu$. This is the longest wavelength that the system can reproduce and it is certainly not very satisfactory. The distortion

of the blue primary is possibly not so objectionable in practice because saturated blues of the same colour as the blue primary are of rare occurrence. Saturated reds are of much more frequent occurrence (e.g., colours 2 and 8).

The green primary is not distorted in colour but it exhibits considerable luminance error. Apart from tending to give colours a fluorescent appearance, there is another unfortunate consequence of the enhanced luminance: if one is to avoid overloading the individual R, G, B channels in the receiver, the peak white must be reduced by a factor depending on the gamut of colours. If the primaries are included, then the factor is 0·53 (i.e., a peak white of 10 ft-L would have to be reduced to 5·3 ft-L). If the thirteen standard colours are taken as limiting the range of colours, then the factor is 0·74.

4. MODIFICATION OF THE NTSC RECEIVER INCORPORATING "ONE-FIFTH SUBCARRIER" CORRECTION

The errors of chromaticity and luminance which are produced when a constant-luminance emission is received on a standard NTSC receiver are considerable (Tables 2 and 3). In Section 4.3 of James and Karwowski's paper, a variant is suggested whereby the green signal is reduced by feeding a fraction of the rectified subcarrier back to the green grid of the colour display tube. For the case of one-fifth subcarrier correction, the results are plotted in Fig. 12 of James and Karwowski's paper. The results for the thirteen colours of Table 1 and Fig. 1 are shown in Fig. 5 and

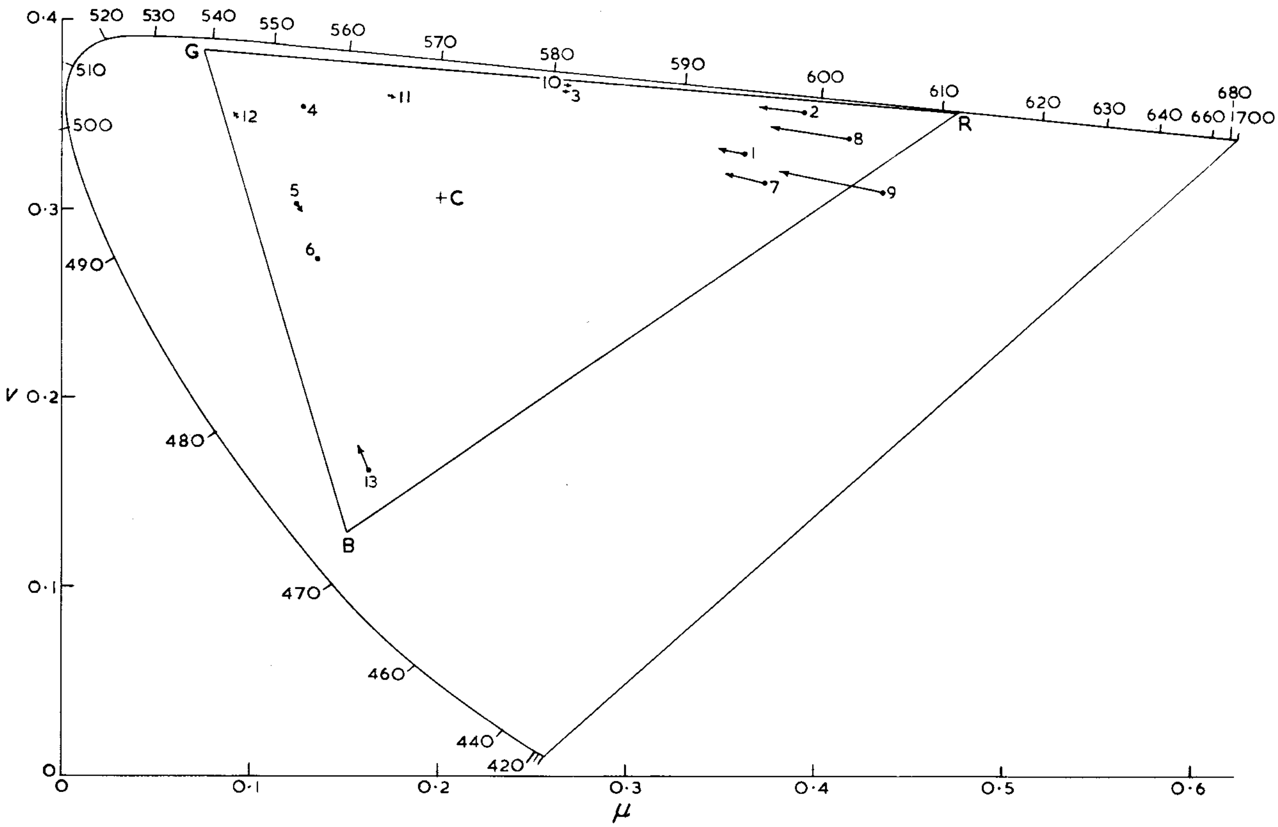


Fig. 5 - Reproduction using ideal analysis, constant-luminance transmission and a NTSC receiver modified to feed back one-fifth rectified subcarrier on to green grid

TABLE 4

Chromaticity and luminance errors for ideal-analysis constant-luminance emission NTSC receiver modified with one-fifth subcarrier correction

Colour	Chromaticity shift in j.n.d's	Luminance shift in j.n.d's
1. Red	3·6	2·8
2. Orange	6·5	4·1
3. Yellow	0·5	0·6
4. Green	0·0	0·0
5. Blue-green	1·6	3·5
6. Blue	0·3	0·4
7. Red	3·1	4·6
8. Red	10·9	3·4
9. Brown	14·8	3·3
10. Yellow	0·5	0·3
11. Green	0·5	0·6
12. Green	0·8	4·6
13. Blue	4·2	3·6
mean	3·6	2·4

Table 4; the analysis is assumed to be perfect in this case (cf. Fig. 3). Undoubtedly there is considerable improvement both in rendering of colour and of luminance. Six of the colours now have less than 1 j.n.d. error in colour (colours 3, 4, 6, 10, 11, 12). The two largest colour errors are now 14·8 j.n.d's (for colour No. 9) and 10·9 j.n.d's (for colour No. 8). Luminance distortion is also considerably reduced, the maximum error is a 22% increase for colour No. 9, which corresponds to about 3·3 j.n.d's for the low luminance of colour No. 9.

From the colorimetric aspect, this subcarrier correction scheme is a fairly good compromise. Two points, however, can be made: (i) the standard NTSC emission with a standard NTSC receiver produces no error of colour or luminance (except for colour No. 9) and (ii) why adopt a "half-way" solution between a standard NTSC receiver and the properly designed receiver for a constant-luminance transmission? The dominant wavelength of the reproduced red primary is now about 601 $m\mu$, which is certainly an improvement over 596 $m\mu$ but it is still an orange rather than a red and is 18 j.n.d's from the original red primary.

5. SIZE OF THE JUST-NOTICEABLE-DIFFERENCE (j.n.d.)

Several investigators[5,6,7] have determined the size of the just-noticeable-difference over the standard colour diagram. When these results are converted to the MacAdam u, v scale the following situation appears:

	approx. mean j.n.d.	size of field	luminance
MacAdam	0·00384	2°	16 ft-L
Wright	0·008	2°	25 ft-L
Judd	0·00035	6°	3-25 ft-L

There is considerable variation in the magnitude of the j.n.d. Without doubt, a large part of this variation is due to differences in the conditions of measurement, such as size of test field (angular subtense), geometrical nature of test field (e.g., bipartite division), presence or absence of surround to test field, brightness of test field and surround field. All these have considerable effect upon the final result. The viewing conditions most relevant to the assessment of colour television pictures have yet to be determined: the j.n.d's of colour difference quoted in the previous sections of this report are all based on the MacAdam figure of 0·00384. Clearly if the conditions were more critical, a smaller unit would be required; however, the present impression is that a larger unit might be more relevant. It will be obvious that the comparison of different systems given in Sections 2.1, 2.2 and 4 is valid independently of the size of unit chosen.

The size of the j.n.d. for luminance variations has been taken from a paper by Hacking:[8] allowance has been made for the brightness of the test colour (assuming a peak white of 10 ft-L) and a condition of adaptation intermediate between low adaptation and high adaptation (curves A and B of Hacking's Fig. 1) has been assumed.

6. ACKNOWLEDGEMENTS

The author wishes to thank his colleagues for helpful discussions and Mr. T.W.J. Crompton for assisting in the colorimetric calculations.

N.B. This report is a transcript of a paper read at a meeting of the Brit. I.R.E. on 14th December 1961.

7. REFERENCES

1. Wintringham, W.T., "Color Television and Colorimetry", Proc. I.R.E., Vol. 39, pp. 1135-1172, October 1951.

2. James, I.J.P., and Karwowski, W.A., "A Constant-Luminance Colour Television System", J.Brit.I.R.E., Vol. 23, April 1962.

3. Breckenridge, F.C., and Schaub, W.R., "Rectangular Uniform-Chromaticity-Scale Co-ordinates", J.O.S.A., Vol. 29, p. 370, 1939.

4. MacAdam, D.L., "Projective Transformations of I.C.I. Color Specifications", J.O.S.A., Vol. 27, p. 294, 1937.

5. MacAdam, D.L., "Visual Sensitivities to Color Differences in Daylight", J.O.S.A., Vol. 32, pp. 247-274, May 1942.

6. Wright, W.D., "The Sensitivity of the Eye to Small Colour Differences", Proc. Phys. Soc., Vol. 53, pp. 93-112, March 1943.

7. Judd, D.B., "Estimate of Chromaticity Differences and Nearest Color Temperature on the Standard 1931 I.C.I. Colorimetric Co-ordinate System", J.O.S.A., Vol. 26, p. 421, 1936.

8. Hacking, K., "The Relative Visibility of Random Noise over the Grey Scale", J.Brit.I.R.E., Vol. 23, April 1962.

BRH

Printed by B.B.C. Research Department, Kingswood Warren, Tadworth, Surrey